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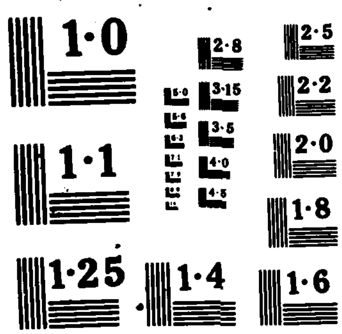
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LARGE OPTICS TECHNOLOGY

FINAL REPORT

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The purpose of this contract was to support and evaluate work done in the area of high-energy laser beam projection systems. Work was performed over the period from April 14, 1980 to December 31, 1984. The principal areas of interest were the support of the DARPA LODE/LAMP/Alpha programs and particularly large optics technology.

The contract was divided into three areas of importance. In the first, the principal investigator participated in reviews of the various project components to provide scientific engineering and technical assistance. Appendix A is a listing of reviews attended. The second area was the preparation of analyses as needed in the various project areas and participation in specific technical meetings, including some proposal review. The third area of interest was the support of related work in the area of optics to provide technical information of importance to specific parts of the high-energy laser program. This latter work primarily consisted of analyses, some of which led to dissertation and thesis work by several students. This final report gives a summary of these latter activities.

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CONTENTS

SUMMARY

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TECHNICAL ASPECTS

Absolute Aspheric Measurement

Important optical topics of interest in high-energy beam direction are the design, tolerancing, and fabrication of large optical components. During the past several years, interest has changed from monolithic large-aperture systems to segmented aperture systems in which the primary mirror is constructed from a number of subapertures that are phased together.

To construct these mirrors, the base radius of the individual segments must be matched. If, as an example, all the segments are a portion of a sphere, then all segments must maintain a radius that varies only to the extent that permits a mismatch leading to a less than tolerable wavefront error at the interface between each section. In the case of a segmented paraboloid, the required match is such that all of the segments are parts of a paraboloid of the same base radius, to within a similar tolerance. In the case of a sphere, it is possible to directly test the segments together by examining the image returned to the common center of curvature of the segments. For the paraboloid, an additional null set of components is required, and some ambiguity can remain, unless appropriate precautions are taken.

An indirect approach to this absolute metrication is the subject of research carried out as part of the requirements for a Masters degree by Carmina Londono-Hartmann (MS, 1982). This work is summarized here, with the full details available in the completed thesis (see Appendix B).

The basic theory of the approach is the recognition that the rate of change of the aberrations with field angle is dependent upon the power of the surface forming the image. In the case of a portion of a segment, there are two principal curvatures, which produce a specific amount of basic astigmatism when the surface is examined near the center of curvature. The image recorded contains an amount of astigmatism that varies

with the square of the field, at least for small object heights. The amount of this variation can be used to determine the amount of curvature in the principal directions of the surface.

In principle, the local curvatures can be obtained from three measurements at three points in the field. In this case, the location of the field points and the amount and orientation of the astigmatism must be known precisely. In practice, a large number of points are taken and fitted to the known functional variation of the astigmatism with field. Since the set of many points determines only a pair of coefficients, the data taking and analysis process acts as a well-defined filter for the data to produce the desired information.

Figure 1 shows the basic test setup. The source is moved along a line, which in the case of a sphere would be the sagittal focus locus. The distance of the tangential focus from the sagittal focus is obtained as a function of the distance from the center of the field.

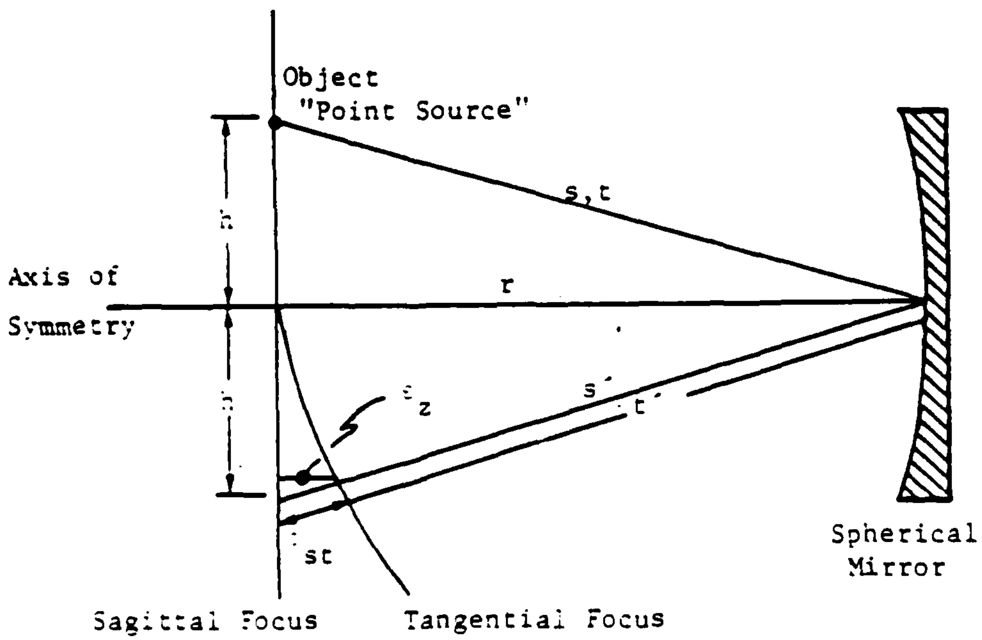

Figure 1. Test setup.

A formula relating the radius to the amount of astigmatism is

$$r = \frac{h}{\epsilon_Z}\left(h + \sqrt{h^2 - 2\epsilon_Z^2}\right). \tag{1}$$

The application to an off-axis parabolic segment is shown in Fig. 2. The analysis for this case is more complex than that for the sphere because the tangential and the sagittal radius must be determined.

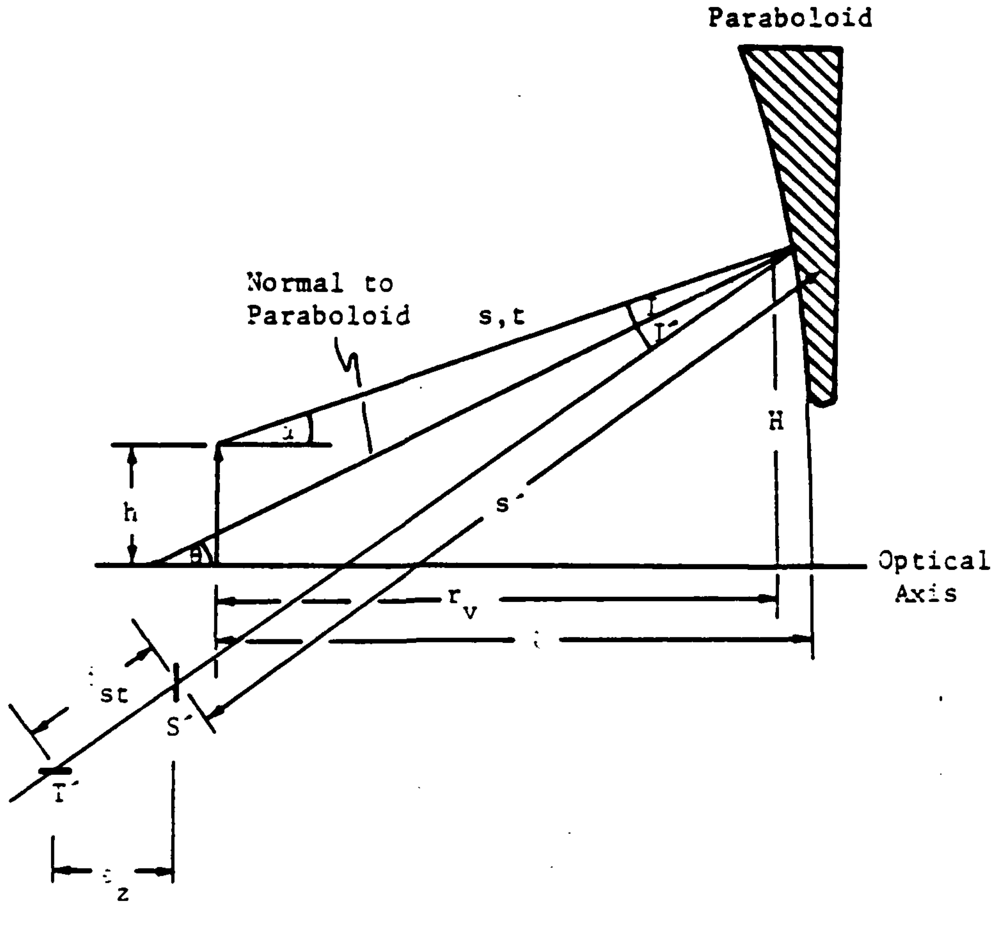

Figure 2. Off-axis paraboloid geometry, Case A.

A laboratory experiment was set up to visually measure the image returned from a sphere. Several observations were made about the difficulty of obtaining alignment of the source, surface, and observing microscope, which affected the accuracy of the measurement. In summary, it was found possible to determine the radius of a sphere to the order of 0.15% by this technique, or about one part in 600.

This level of accuracy is good for a totally remote measurement, but it is not adequate for the intended application. It was felt that significant improvements in the accuracy could be achieved if more data were taken, and if interferometric methods were used to eliminate the measurement uncertainty due to the depth of field of the visual measurement.

A detailed analysis of the measurement of a paraboloid section was carried out by computer modeling. The returning wavefront from a paraboloid observed at the center of curvature contains a large amount of spherical aberration that would have to be removed from the measurement. This is possible if all of the test conditions contain well defined coordinates and mensuration. Several test configurations were examined, including direct examination at the center of symmetry of the segments, and retroreflection by a moderate size sphere at the radius location.

The most practical approach was the examination of a central portion of the segment, treating it as a centered component. A calculation from ray trace data shows the possibility of determining the sagittal radius of the segment to the extent possible from round-off error in the computer program doing the data fitting to the ray trace data. This indicates that, theoretically, the calculation is possible. No experiment to demonstrate this was carried out. It is likely that accuracies similar to those for a sphere would be expected.

Effect of Coatings on Aberrations

The effect of high-reflectivity multilayer stacks on the aberrations arising at a reflecting surface is the subject of dissertation research by R. Knowlden (PhD, 1981). The problem addressed and the work performed are summarized here. The details are contained in the dissertation (see Appendix C).

The typical primary mirror used for a chemical laser system may be of the order of 4 m in diameter, f/1 or f/1.5, with coatings to produce reflectivities of greater than 0.999 at 3.8-μm wavelength. A typical goal for allowable wavefront error from the coating is about 0.02 wavelength, RMS.

Physical problems can be produced by such coatings. Specifically, the shape of the mirror can be changed due to stresses produced in the coating. The subject of this study was to determine the intrinsic optical effect produced by a multilayer stack, even if no dimensional errors are present.

There are two sources of wavefront error that can be obtained from a multilayer stack. Even a perfect stack will produce a wavefront error on a primary mirror because of the progressively varying angle of incidence across the mirror. Any multilayer stack will be fabricated with some tolerance regarding the thicknesses of the layers. Usually, the tolerance buildup is adjusted to keep the reflectivity within stated limits, but the phase error from the multilayer can be such as to produce a varying wavefront error.

In addition, if the wavelength is changed, the wavefront curvature that will be obtained from the coating will change. An auxiliary problem is that of measuring the coated surface in the visible, where convenient optical figure measurements can be made, and inferring the probable error to be found in the infrared. In the work carried out, Knowlden shows techniques for determining which coating designs will be relatively insensitive to wavelengths in the visible in order to calibrate the effect of the coating on the wavefront in the infrared operational wavelength.

On a strongly curved mirror, such as an f/1.5 paraboloid, the effect of varying the angle of incidence across the aperture may be significant. For example, errors of the order of 0.08 waves can be obtained from a broadband all-dielectric coating. A simple enhanced silver coating will produce an intrinsic error on the order of 0.002 wave, which is usually negligible. In general, coating errors due to nonuniformities are more significant than the intrinsic errors.

As an example of this error, a six-layer enhanced reflector at 3.8 μm with 1% layer thickness errors will produce about 0.01 wavelength of RMS wavefront error. In general, adequate control of reflectivity will produce reasonable control of the wavefront error.

Techniques can be developed for estimating the performance of an infrared coating from measurements in the visible. Ambiguities in such a test that arise from errors on the surface or compensating errors in the coating must be removed. Methods for doing so by using a number of visible wavelengths or by doing best fits to a known design have been investigated. A simple technique for extrapolating the infrared wavefront from a number of visible measurements when proportional errors are presumed in the coating thickness was developed. Interferograms are made of the mirror at three visible wavelengths, and the infrared wavefront error due to the coating is determined in a way that is insensitive to any error caused by distortion of the substrate, or even to fairly large errors in the alignment of the optical testing system.

Modeling of Errors in Systems

When several optical surfaces are combined in an optical system, there is the possibility of errors from the surfaces combining in such a way that simple wavefront addition does not take place. One well known example is the testing of a nearly flat optical surface at a large angle of incidence when combined with a large test sphere.

The aberrations from the flat are greatly affected by the high angle of incidence and can actually be used to provide an absolute measure of the curvature of the flat surface.

K. L. Shu (PhD, 1982) examined several problems of this type in his dissertation research. The problem of the Common test for flat testing and the effects of misalignments in Ritchey-type Cassegrains were some of the problems examined. A summary of the work will be given here, with the details available in his dissertation (see Appendix D) and in a published paper in Applied Optics.

The effects of misalignments and combination of surfaces were examined using exact ray tracing. The surfaces were traced by including a generalized description of the surface in terms of Zernike terms to fit the errors of the surface. By doing so, the effect of a predicted error on the surface when the surface was used in an actual system can be inferred. Since the exact combination of such errors in a system does not add linearly due to possible nonrepeating paths through the system during a test, an iterative technique can be used to find the best fit of the actual errors on the surface to the measured wavefront error.

Several simple systems were used as examples. In the prediction of system error a Ritchey-Chretian system and a reflaxicon, as found in a unstable laser cavity, were studied. It was shown that a correct alignment to compensate certain surface figure errors in the system can be obtained. This has the desirable effect of permitting larger errors of certain classes on the components of the system.

In the testing of optics, a method was found to separate the figure errors from the alignment errors. An off axis test configuration, the Ritchey-Common test was studied in detail. An iterative figure determination approach was suggested and compared with other more usual methods for reducing the measured wavefront error.

Extrapolated Mean Square Methods

The design of optical systems and the iterative fitting of any system of data to a weighted mean square set of targets require the use of iterative computational methods. The dissertation work of E. Huber (PhD, 1983) was partially supported under this contract (see Appendix E).

In his work Huber developed a technique for using the effect of highorder derivatives to guide the path of solution for a set of nonlinear equations. A practical example of the application of this technique is lens design. In lens design the equations are not known explicitly, but are obtained from successive ray tracing as the system parameters are changed iteratively in an attempt to find a solution.

Subaperture Testing

When a large aperture optical system is to be tested, the test optics, either collimator or retroreflective flat may cost as much as the system to be tested. The possibility of testing by the use of an array of smaller flats has been proposed. The practical analysis and testing of such a method of testing was carried out by T. Stuhlinger (PhD, 1984) as his dissertation work. The analysis of the problems and some of the analysis of test data were supported by this contract. The actual experiments were carried out under other funding at the Air Force Weapons Laboratory. Details are available in the dissertation (see Appendix F) and in a paper submitted for publication in Applied Optics.

The construction of large optical systems with apertures of the order of 10 meters in diameter or larger requires testing with very large optics, if the entire aperture is to be tested simultaneously. A suggestion was made by J. Thunen and O. Kwon of Lockheed that an array of "noncoherently" related flats could be used for this purpose. The testing is done by distributing an array of these subaperture sized flats across the

aperture. The partial data on the wavefront obtained from the regions of the apertures of the flats are extrapolated to determine the wavefront over the entire aperture of the telescope.

It was the purpose of this work to determine that the experimental possibilities for this approach supported the theoretical predictions for the process. Two reconstruction algorithms using Zernike polynomials had been suggested by various investigators. A third method was developed which provides raw phase data over the aperture of the system under test.

The experiment used a 6-in. diameter array of seven subapertures. Data were obtained with this array under various conditions and were compared with the true full-size aperture of the interferometer.

Data were taken and compared with the calibrated wavefront error and were found to be in good agreement. The deliberate introduction of atmospheric turbulence was shown to significantly affect the accuracy of the extrapolated results.

In general, it was shown that for the configuration chosen, the extrapolated data were about five times less accurate in predicting the full-aperture wavefront error than a direct full-aperture measurement. But it is to be noted that the tilts of the subaperture flats were not recorded in this practical simulation, and were, therefore, unknown.

The conclusion is that the subaperture testing functions in the absence of subaperture phasing. There is a tradeoff of data points versus the accuracy of the extrapolation of the results. Algorithms using either Zernike coefficient fitting or raw data fitting were found to function about equally well.

APPENDIX A

PERTINENT TRAVEL AND REVIEWS ATTENDED UNDER THIS CONTRACT

Date	Destination	Purpose
8/12-8/14/80	Palo Alto, CA	Meetings at LockheedNOAA projects and DARPA review
8/19-8/21/80	Boston, Norwalk, CN White Plains, NY Rochester, NY	DARPA review meeting at ITEK, Perkin-Elmer, and Kodak
9/4/80	Los Angeles	DARPA LODE meetings
10/11-10/17/80	Chicago	OSA Conference
12/8-12/18/80	Washington, DC	DARPA meetings
1/18-1/20/81	San Jose	SPIE meeting on diamond turning
1/26-1/30/81	San Francisco, San Jose, Burbank, Los Angeles	DARPA meetings at Lockheed and Hughes Aircraft
2/2-2/4/81	Denver	Conference on Guidance and Control
3/1-3/5/81	Washington, DC	DARPA meetings
3/17-3/18/81	Washington, DC	DARPA meetings
4/5-4/8/81	Danbury, CT Lexington, MA	Large optics meeting
4/6-4/10/81	Santa Fe, NM	LASL Conference on Optics "81"
4/19-4/23/81	Washington, DC	SPIE meetings
5/13-6/7/81	Stockholm, Frankfurt, Paris Los Angeles	Meetings at Reading Univ. Imperial College, Schott Glass, Amersil Hereaus, Institute d'Optique Meetings at JPL
6/5-6/7/81	Albuquerque	DARPA LODE meetings
6/29-7/1/81	Albuquerque, NM	Conference at AFWL, optical testing
8/28-9/17/81	Munich, London, Austria	Present paper and Chair for Optics meeting. Technical discussions at Zeiss and ESO Imperial College and NPL, London

8/21-8/27/81	San Diego, CA	SPIE Conference, executive committee meeting and board meeting to receive an award.
10/5/81	Palo Alto, Culver City	Project meeting at Lockheed and Hughes Aircraft
10/25/81	Kissimmee, FL	OSA Conference
11/30-12/2/81	Albuquerque, NM	Lifer meeting, BDM Corp.
12/7-12/11/81	Los Angeles	Review LODE meeting at Hughes
12/13-12/19/81	Palo Alto, CA	Palo Alto review, LODE meeting at Lockheed
2/14-2/27/82	San Francisco, CA	DARPA, selection review meeting
4/5-4/8/82	Danbury, CT	Attend LAMP project kick-off meeting
	Lexington, MA	
5/11-5/24/82	Rochester, NY	OSA Conference
9/4/-9/21/82	Palo Alto, CA	LODE review
9/28-9/29/82	Albuquerque, NM	DARPA Meeting
11/26-11/27/82	Los Angeles Washington DC	SPIE symposium DARPA meeting
12/1-12/3/82	Palo Alto, CA	DARPA review at Lockheed
1/14/83	Albuquerque, NM	DARPA Subaperture testing program meeting
1/18-1/20/83	Los Angeles	SPIE meeting, Meeting at Hughes
2/7-2/10/83	Sunnyvale, San Jose, CA	DARPA LODE program review
3/13-3/24/83	Newark, Boston	Source selection Board for DARPA
6/24/83	Pittsburgh, PA	LODE Brassboard Fabrication meeting
7/22/83	San Francisco, CA	AFWL LODE Interim design review meeting
8/26/83	San Diego, CA	SPIE Conference
9/7-9/8/83	Albuquerque, NM	DABM technology panel meeting at Kirtland AFB

9/26-9/28/83	San Francisco, CA	LODE PDR meeting at Lockheed
10/16-10/22/83	New Orleans, LA	To attend OSA conference
11/15-11/17/83	Palo Alto, CA	LODE meeting
11/29/83	Albuquerque, NM	DARPA LODE meeting at Kirtland AFB
12/20/83	Kirtland AFB	LODE meeting
1/25-2/3/84	Maui, Hawaii, Oakland, CA	LODE off-site meeting and laser mirror reliability

APPENDIX B

ABSOLUTE MEASUREMENT OF RADIUS OF CURVATURE

by

Carmiña Londoño-Hartmann

A Thesis Submitted to the Faculty of the

COMMITTEE ON OPTICAL SCIENCES (GRADUATE)

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

1 9 8 2

ABSTRACT

A method to obtain an absolute measure of the radius of curvature of off-axis paraboloids was investigated. The principle used was the measurement of the variation of astigmatism with field that is present for conjugates near the center of curvature of a reflecting surface. The principle was tested in the laboratory with a sphere and the results are discussed. The feasibility of implementation to off-axis paraboloids was studied with a computer model. Observations for both single-pass and double-pass are made.

APPENDIX C

WAVEFRONT ERRORS PRODUCED BY MULTILAYER THIN-FILM OPTICAL COATINGS

by

Robert Edward Knowlden

A Dissertation Submitted to the Faculty of the

COMMITTEE ON OPTICAL SCIENCES (GRADUATE)

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

1 9 8 1

ABSTRACT

The mirrors used in high energy laser systems have at least two requirements that are uncommon in optical engineering: the reflectance of such mirrors must be very high (> 0.999), and the level of aberrations introduced by the mirrors is desired to be very low, typically $\lambda/50$ peak at 3.8 μ. The first requirement can be met by using multilayer thin film coatings, but such coatings can themselves produce aberrations in an optical system.

One possible effect in multilayers is that such coatings produce an optical phase change on reflection that varies with angle of incidence and polarization of the illuminating beam. On a strongly curved mirror, such as an f/1.5 parabola used as a collimator, these effects may be appreciable for some coatings (e.g., $\lambda/13$ for a broadband all-dielectric reflector), but for an enhanced silver coating the effects are small, typically $\lambda/400$ of error that is almost entirely in the form of a small focus shift. If this same parabola is tested at its center of curvature, the coating-caused aberration due to angle of incidence effects are nearly zero (e.g., $\lambda/50{,}000$ for the broadband reflector that gave $\lambda/13$ when the parabola was used as a collimator). The wavefront errors due to coating nonuniformities are usually more important than angle of incidence effects.

The simplest type of coating nonuniformity to analyze is a proportional error, i.e., an error where the ratios of the thicknesses

of the layers are fixed but the thin film stack varies in total thickness across a surface. For a six-layer enhanced reflector for use at 3.8 μ, a 1% thickness error produces an approximate λ/100 wavefront error. At visible wavelengths, however, the aberration produced by such a coating error can be very different because of the optical interference nature of the coating.

Means may be developed to estimate the performance of such an infrared reflector from measurements at visible wavelengths. If the errors produced by the coating are to be distinguished from those existing in the test due to misalignment or gravitational flexure of a large mirror, two or more wavelengths must be chosen. There are ambiguities in such a test that may be resolved by choice of an appropriate coating design or by using enough wavelengths in the visible, and both means have been studied. A technique was found where the infrared wavefront can be determined for a coating with proportional thickness errors if the coating prescription is known: interferograms of the mirror are made at three visible wavelengths, and the IR wavefront error due to the coating error is determined in a way that is insensitive to any errors caused by distortion of the substrate or even fairly large misalignments in the optical test of a mirror's figure.

Simulations of some real coatings have determined that additional work needs to be done to improve the analysis procedures used in estimating the infrared performance of an enhanced reflector from visible light measurements. However, initial results show that fairly accurate predictions of the IR wavefront errors can be made from measurements of infrared enhanced reflectors in visible light.

APPENDIX D

ANALYSIS OF ALIGNMENT AND SURFACE FIGURE ERRORS IN OPTICAL SYSTEMS

by

Ker-Li Shu

A Dissertation Submitted to the Faculty of the

COMMITTEE ON OPTICAL SCIENCES (GRADUATE)

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

1 9 8 2

ABSTRACT

The effects of alignment and surface figure errors and their compensation with each other in optical systems are analyzed based on computer simulations with exact ray tracing data. These effects are included in the prediction of system performance and the testing of optics. Several simple systems are used as examples. In the prediction of system performance, a Ritchey-Chretien telescope and a Reflaxicon system are studied. A correct alignment can be found to compensate certain surface figure errors in the system. This will allow larger surface figure errors to be tolerated in the system. In the testing of optics, a method to separate the figure errors from the alignment error contributions is discussed and an off-axis test configuration, the Ritchey-Common test, is studied thoroughly. A figure design approach is suggested and compared with other approaches for reduction of the measured wavefront data in the Ritchey-Common test.

APPENDIX E

EXTRAPOLATED LEAST SQUARES OPTIMIZATION APPLIED TO LENS DESIGN

by

Edward David Huber

A Dissertation Submitted to the Faculty of the

COMMITTEE ON OPTICAL SCIENCES (GRADUATE)

In Partial Fulfillment of the Requirements
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In the Graduate College

THE UNIVERSITY OF ARIZONA

1 9 8 2

ABSTRACT

A new approach to least squares optimization has been developed which uses extrapolation factors to introduce variable metric techniques into the least squares optimization methods used in optical design. This new approach retains derivative information between successive optimization iterative steps to form approximate second derivatives in order to develop extrapolation factors. These extrapolation factors are used to update and refine important system parameters including the merit function, the first derivative matrix and the system metric without requiring the reevaluation of the system derivatives. This extrapolated least squares (ELS) optimization method does not simply add damping terms to the diagonal elements of the system metric to control optimization step lengths as is done in the various damped least squares (DLS) optimization methods; but the total system metric is updated to reflect the current optimization progress made to within the limit of the extrapolated quadratic approximation to the problem. The ELS and conventional least squares optimization methods are compared in numerous optimization problem examples including several test functions as well as typical optical design problems. The extrapolated least squares (ELS) optimization method is shown to reduce computational overhead and to accelerate convergence of least squares types of optimization problems.

APPENDIX F

OPTICAL TESTING OF LARGE TELESCOPES USING MULTIPLE SUBAPERTURES

by

Tilman Werner Stuhlinger

A Dissertation Submitted to the Faculty of the

COMMITTEE ON OPTICAL SCIENCES (GRADUATE)

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

1 9 8 4

ABSTRACT

The construction of telescope systems with large apertures (≈10 meters) is currently being planned. These entire telescope systems should be optically tested in a double-pass configuration. The high cost of manufacturing optical flats large enough to test a large telescope has stimulated research on a new type of testing in which several smaller flats, or subapertures, are distributed over the telescope aperture. The problem is to combine the partial data obtained only over the subapertures in order to obtain the wavefront over the entire aperture. It was the purpose of this dissertation to prove experimentally that subaperture testing is feasible. The question of the necessity of phasing the subapertures relative to each other was specifically addressed in the experiment.

In chapter 2, a brief review is given of two algorithms, utilizing Zernike polynomials, developed by other investigators. A third subaperture testing analysis algorithm, the Stuhlinger method, is developed in this work; this provides raw phase data over the entire aperture of the system under test. A statistical analysis of this algorithm is given.

The experimental apparatus and plans are discussed in chapter 3. A 6 in. diameter array of seven subapertures was used in this small-scale test. Data were obtained with the array, a monolithic flat, and a mask simulating the array placed over the monolithic flat.

The results of the experiment, presented in chapter 4, are in good agreement with control data measured with a Zygo interferometer. Data and analysis for the Stuhlinger method are also presented. Data taken with atmospheric turbulence deliberately introduced show that, in the presence of turbulence, subaperture testing is significantly less accurate than conventional testing.

Error analysis given in chapter 5 shows that Zernike coefficients derived using subaperture testing are 5 times less accurate than those derived using monolithic testing for the subaperture configuration used here. It is shown that knowledge of the subaperture tilts can produce accurate wavefront information with as few as 30 data points per subaperture, as compared with 750 data points per subaperture if tilts are unknown.

Conclusions are stated in chapter 6. Subaperture testing indeed functions in the absence of subaperture phasing. Tilt information influences mostly the lower order Zernike coefficients; lack of such information may be compensated by the use of more data points. Algorithms yielding either Zernike coefficients or raw phase data were shown to function.

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